

UNPUBLISHED PRELIMINARY DATA

NASA CR-50928

16p  
FINAL REPORT

National Aeronautics and Space Administration  
Research Grant NsG-264-62

FACILITY FORM 602	N65 14654	
	(ACCESSION NUMBER)	(THRU)
	16	
	(PAGES)	(CODE)
	CR-50928	13
	(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

Covering the Period  
November 1, 1962 - June 30, 1963

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July 15, 1963

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GPO PRICE \$ \_\_\_\_\_

OTS PRICE(S) \$ \_\_\_\_\_

Hard copy (HC) \$1.00

Microfiche (MF) \$0.50

## I. INTRODUCTION

Under the National Aeronautics and Space Administration Research Grant NsG-264-62, awarded for one year on May 1, 1962, and subsequently extended to June 30, 1963, the Research Laboratory of Electronics of the Massachusetts Institute of Technology started a program to study the resonance lines of molecular oxygen in the terrestrial atmosphere at 5-mm wavelength. Microwave propagation in the earth's atmosphere is dominated by the molecular resonances of water vapor and oxygen. As a result, these resonances have been studied to determine their effect upon propagation, but very little use has been made of these lines as a tool to determine the physical structure of the atmosphere. The water-vapor line can be detected and studied by ground-based observations, because of the low abundance of water vapor. Oxygen, on the other hand, is so abundant that the atmosphere is completely opaque in the center of the resonances. Thus studies of these lines requires the use of high-altitude aircraft or balloons to transport the observing equipment above most of the atmosphere.

The theoretical development of thermal emission from molecular oxygen in the atmosphere indicates that studies of these lines afford a new and competitive means of probing the physical structure of the atmosphere. Such studies are expected to be particularly fruitful when performed from an earth-orbiting satellite. The experimental observations in support of the theory are, however, practically nonexistent, and it is desirable to verify the theoretical predictions through balloon flights before a satellite experiment is contemplated. Accordingly, the basic objective of the M.I.T. program is to provide experimental verification of the theoretical spectrum.

Furthermore, the constraints of equipment, such as weight, power, reliability, etc., are considerably relaxed for balloon flights as compared with satellite operations; therefore a balloon program affords an ideal means of proving equipment design under operational conditions. Accordingly, a second objective of the M.I.T. program is to design and perfect spectral-line radiometers operating at approximately 5-mm wavelength for spacecraft operation.

## II. MAJOR ACCOMPLISHMENTS

### A. Construction of Equipment

During the first year of the program, effort has been directed toward constructing a radiometer suitable for balloon flight. The theoretical part of the program, described in the following section, served to define the experiment to be performed and dictated several important equipment parameters. The system that has been designed and built consists of a three-channel radiometer to measure thermal emission from the molecular oxygen line at 61,151 Mc/sec and to determine, in a preliminary way, its linewidth, intensity, and dependence on antenna zenith angle. The system is a Dicke superheterodyne radiometer with three IF amplifiers having center frequencies of 20 Mc/sec, 60 Mc/sec, and 200 Mc/sec. To avoid duplication of circuitry, the IF amplifiers are time-shared with the low-frequency amplifiers, synchronous detector, and recorder. The system takes advantage of the expected symmetry of the resonance line, so no image rejection is employed. With the local oscillator tuned to 61,151 Mc/sec, the radiometer will be responsive to signals in the frequency ranges shown in Table 1.

Table 1. Passbands of Radiometer.

<u>Channel</u>	<u>Passbands</u>	
1	61, 126-61, 136 Mc/sec	61, 166-61, 176 Mc/sec
2	61, 086-61, 096	61, 206-61, 216
3	60, 943-60, 959	61, 343-61, 359

This technique was chosen because we wished to avoid the complications that would arise from frequency-scanning the local oscillator across the resonance. In subsequent flights, we may introduce this feature.

In addition to spectral intensity information, it is important to obtain knowledge on the dependence of intensity with zenith angle. Ideally, this could be obtained by slowly scanning the antenna from the nadir to the maximum elevation allowable by the constraint of the fully inflated balloon, but this seemed an unnecessary sophistication for the initial flights. An alternative approach, which has been adopted, is to time-share the radiometer between two 6-inch parabolic antennas oriented at zenith angles of 60° and 75°. This should provide preliminary information on the intensity variation with zenith angle and will serve to dictate future experimental requirements.

The radiometer is calibrated by means of a thermal match load maintained at a preset temperature of approximately 400° K. In addition, the temperature of the matched load on the ferrite chopper is recorded. Thus two reference temperatures are monitored so that both the radiometer sensitivity and base line may be calibrated in temperature units.

The local oscillator was to be a solid-state device utilizing varactor multipliers; however, development on this phase of the program has not progressed sufficiently to meet the flight schedule. Therefore a klystron (OKI Type 60V10) has been incorporated in the initial flight package. The tube is operated in an oil bath and controlled in frequency by a servo-loop from a reference cavity tuned to 61,151 Mc/sec.

The time-sharing is controlled by a central clock and programmer with a basic period of approximately 1 minute. A 9-position program is required for three IF channels. Programming is as follows: The 60° zenith angle antenna is connected to the radiometer for 3 minutes, during which each IF channel is sampled for 1 minute. This is then repeated for the 75° zenith angle antenna and the calibration load. The total cycle is repeated at 9-minute intervals.

Using a balanced crystal mixer, we have measured noise figures of approximately 15 db, 17 db, and 21 db for the 20 Mc/sec, 60 Mc/sec, and 200 Mc/sec channels, respectively. A 10-second integration time is planned for all channels, thereby giving rms temperature fluctuations of between 2° K and 10° K in the outputs, the amount depending on the channel.

All data will be recorded in flight on magnetic tape. For this purpose, a special slow-speed recorder has been obtained (Lockheed Electronics Company, Model 411F, modified) to allow 8 hours of data storage.

A block diagram of the radiometer is shown in Fig. 1.

The total weight of the flight package, including gondola, will be approximately 335 pounds. The radiometer, exclusive of batteries and magnetic tape recorder, weighs 45 pounds; the battery pack, capable of supplying 5 amps for 8 hours at 28 V.D.C., weighs 40 pounds; the magnetic tape

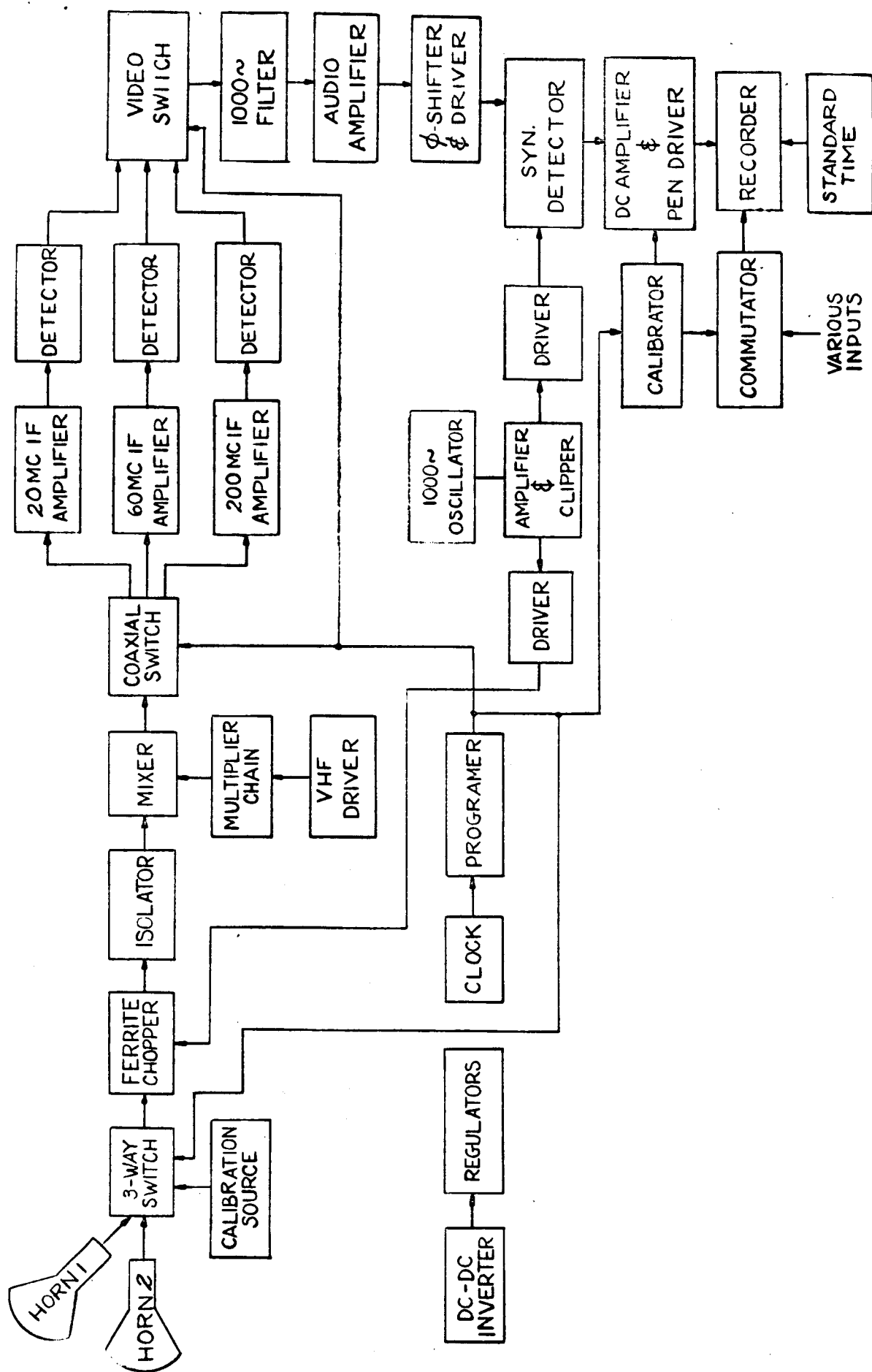


FIG 1. BLOCK DIAGRAM OF RADIOMETER

recorder and shock-mounted case weighs 50 pounds. The gondola measures 30" X 38" X 27" and weighs approximately 200 pounds.

#### B. Theoretical Spectra

The microwave properties of molecular oxygen have been rather extensively studied by the techniques of laboratory spectroscopy, and the results obtained thereby form the basis for the theoretical predictions of the spectra of molecular oxygen in the terrestrial atmosphere. Such studies are usually made, however, at low pressures and in pure oxygen — two conditions that are not generally applicable to the earth's atmosphere. Sufficient measurements have been made to enable one to make estimates of the effects of foreign gases, principally nitrogen, and of pressures between 0.1 atm and 1 atm. Therefore it is possible to make computations of the expected microwave spectra, within the limitations of the uncertainties mentioned.

The theoretical spectra of molecular oxygen in the atmosphere can be computed by integrating the equation of transfer with suitable allowances for the variation of temperature, pressure, and chemical composition with altitude. This necessitates adopting a model for the physical structure of the atmosphere, and the ARDC standard atmosphere has been chosen. The linewidth of the resonance lines will be largely dominated by pressure broadening throughout most of the atmosphere, but there will be a height at which the pressure is so low that other broadening mechanisms can no longer be neglected. For example, the Zeeman splitting of the oxygen lines as a result of the terrestrial magnetic field will be comparable with the pressure broadening at heights of 40-50 km, and Doppler broadening should be included for heights in excess of 50 km. Since these effects are expected to be important for satellite experiments, and our initial balloon flights are not to exceed 30-km altitude, the theoretical spectra

computed thus far have included only pressure broadening.

A program for the IBM 7090 computer has been written which calculates the total attenuation and the thermal emission throughout the atmosphere in the frequency range of the molecular oxygen lines. The program is adaptable for any altitude up to 40 km, for any zenith angle between  $0^\circ$  and  $180^\circ$ , and for any desired frequency range and increment. Preliminary computations have been confined to the  $N = 9^+$  line at 61,151 Mc/sec, since this is the subject of the present experimental program. Figure 2 depicts the results obtained for the oxygen emission at 30 km for various zenith angles. The results of the computations have been used to determine the equipment parameters of the receiver and will be extensively used in the data interpretation phase of the program after successful flight.

### C. Observing Program and Flight Schedule

We plan to take advantage of the Balloon Flight Facility of the National Center for Atmospheric Research (NCAR), Palestine, Texas, for all launch, flight, and recovery operations. Negotiations with NCAR have been underway for some time to insure complete compatibility between their launch capabilities and schedule and our requirements.

It is planned to have a flight of approximately 8 hours' duration, of which 4 hours will be spent at float altitude (nominally, 100,000 feet). An important part of the experiment is to acquire data during ascent and descent whenever possible. This will be invaluable for judging the performance of the over-all system, providing interchannel comparisons, and comparing the observations with the theoretical predictions for heights between 0 km and 30 km.

The first flight is expected to be an over-all checkout of the equipment.



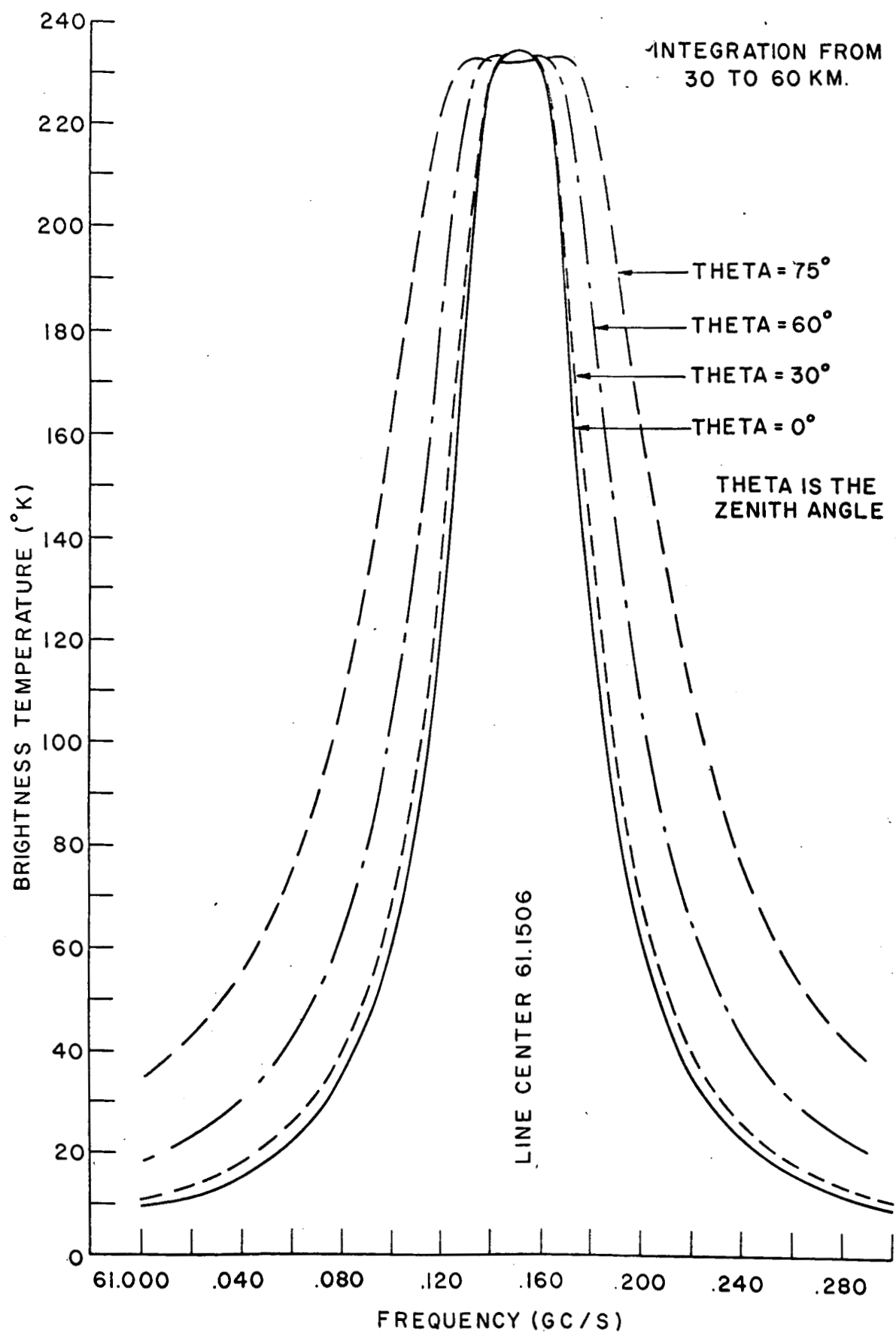


FIG. 2 MOLECULAR OXYGEN LINE AT 61,151 MC/S AT AN ALTITUDE OF 30 KM

and our observational approach to the problem. No altitude stabilization is being incorporated because we are not aiming the antenna beams at any celestial object. The pendulous motion at float altitude is expected to be only a few minutes of arc in elevation. Since the antenna bandwidth is  $2^\circ$ , this effect will be negligible. During ascent and descent, turbulent motions will cause considerably greater motion when passing through the tropopause, and data taken at that time may be useless. Slight oscillations in azimuth may occur at float altitude, and these will be scientifically interesting if they give rise to an azimuth variation in thermal emission.

The initial flight is scheduled for August 8, 1963. Subsequent flights depend critically on the success of the NCAR payload recovery program and the equipment damage sustained in landing. Although the first flight is to be a daytime flight, it is hoped some future flights will include night launches.

### III. UNSOLVED PROBLEMS

#### A. Solid-State Local Oscillator

It was our initial intent to build the radiometer entirely of solid-state components to conserve weight and power. But it soon became apparent that a solid-state local oscillator could not be developed in time for the first series of flights without imposing a serious delay in the flight schedule. Although an alternative source of microwave power is to be used in the initial observations, it is highly desirable to continue work toward the realization of a solid-state local oscillator providing approximately 3 milliwatts at 5-mm wavelength. At present, a source of power at

61,151 Mc/sec has been built, using varactor multipliers from approximately 7,500 Mc/sec, but the over-all efficiency is too low to permit its use as a local oscillator. The device has been used, however, to set the reference cavity in the frequency stabilization network for the klystron to be used in the flight model.

A solid-state local oscillator is now being built with a 30,000-Mc/sec output for another NASA-sponsored radiometer. It is expected that this multiplier chain, with another stage of frequency doubling, will prove suitable for subsequent flights. This will allow a reduction in weight and power required for operation, and is mandatory for any application to space vehicles.

#### B. Telemetry

Present flight plans call for recording all data on board during the flight on a magnetic tape recorder. This has added considerably to the over-all weight and also forced an increase in the size of the gondola. Furthermore, the entire success of the mission is dependent upon recovery of the equipment after landing, since no scientific data are being telemetered to the ground.

Preliminary flight plans included a provision to telemeter all scientific data, but it was discovered that the frequency chosen for this coincided with that of NCAR's balloon launch contractor for commands to the balloon. Since the two were incompatible and time did not permit construction of equipment at a different frequency, the decision was made to record data on board. It is hoped that subsequent flights can include telemetry of scientific data, thereby reducing the payload weight and size and raising the probability of success of the mission in spite of problems encountered in recovery operations. In this connection, NCAR is establishing fixed and mobile telemetry ground

stations and may supply future experimenters with complete telemetry equipment.

### C. Data Interpretation

The basic objective of the experimental program is to provide an observational check on the existing theory of thermal emission from the molecular-oxygen lines. It is expected that the measurements if successful will provide the first step toward this goal; however, it is of interest to inquire how the measurements can be utilized to provide detailed information on the physical structure of the atmosphere. Such an undertaking will require the mathematical inversion of two integral equations one of which relates the measured emission to the antenna pattern and the actual emission, and one that relates the actual emission to the physical properties along the antenna beam. The former is a common problem in radio astronomy, but the situation here does not resemble that actually encountered because the entire antenna is immersed in the emitting region, the atmosphere. In some respects, that will simplify the problem, particularly for those frequencies and altitudes for which the attenuation is large so that all of the detected emission must originate in the immediate surroundings of the balloon. This also simplifies the solution to the second integral equation because the path length over which the integration must be performed is very small, and the physical parameters, such as temperature and pressure, will vary only slightly.

To interpret the data properly, it will be helpful to measure the atmospheric temperature and pressure as a function of altitude during the flight. This requires radar tracking, or an on-board radar altimeter, to determine the altitude independently of pressure, that is, without resorting to an aneroid barometer. Preliminary flights will not have the advantage of

a radar altimeter, but it might be incorporated in future flights if the analysis indicates it to be desirable.

#### IV. SUGGESTIONS FOR FUTURE RESEARCH

Several areas of future research follow as logical extensions of the work begun in the program described above. These fall into the distinct classifications of experimental, theoretical, and observational operations.

##### A. Equipment Modification and Improvement

In Sections II and III mention was made of several possibilities for improving the equipment or modifying the experimental technique. Worthy of specific mention here are:

1. Frequency-Scanning Local Oscillator. A thorough investigation of the molecular-oxygen resonance lines should include detailed spectral information, which can be obtained either by frequency-scanning techniques or by use of multiple channels. For simplicity, we have chosen the latter, but with only three rather widely spaced channels. An ideal experiment would repeatedly scan a line in a time consistent with the equipment parameters, such as time constant and bandwidth, and consistent with the observational situation, such as vertical motion of the balloon, zenith angle, altitude, etc. Such a program requires a variable-frequency source of microwave power and, to conserve weight and power, such a source should be a solid-state multiplier chain. This would allow the actual frequency scanning to be done at a low frequency, typically 100-500 Mc/sec, in such a manner that when multiplied to 60,000 Mc/sec the scanning range is approximately 500 Mc/sec.

2. Antenna Beam Scanning. Another equipment improvement would be to incorporate an antenna beam-scanning program in the observations. Actually, this would represent a minor modification of present equipment. If frequency scanning is also performed, the antenna scanning must be step-wise and coordinated with the frequency scanning, or it becomes impossible to separate intensity variations as being due to beam or frequency scanning.

3. Lightweight Radiometers. Preparatory to constructing satellite equipment, all attempts should be made to reduce the weight and power requirements of existing equipment. As already mentioned, a solid-state local oscillator and provisions for data telemetry are immediate steps that can be taken. Further progress can be made in the use of "thin-film" electronics for the various low-frequency circuits.

#### B. Theoretical Research

In connection with more sophisticated balloon flights, and certainly before satellite experiments, the theory of thermal emission from the molecular-oxygen resonance lines must be investigated, due allowance made for Doppler motion and Zeeman splitting at high altitudes. Of particular importance, the line splitting resulting from the geomagnetic field may be of sufficient magnitude that geomagnetic effects in the upper atmosphere could be monitored by this technique.

A further aid to the interpretation of observational data would be an investigation into the effects of foreign-gas broadening on the oxygen lines as a function of temperature and pressure. Furthermore, line-to-line variations should be considered. This is a difficult theoretical problem and, ideally, should be coupled with a laboratory investigation.

### C. Observational Programs

Future observational efforts can be as varied as the imagination of the experimenter, but several broad areas of development are obvious. These are feasible, at present, with existing equipment, or with equipment that may be possible in the near future.

1. Solar Absorption Experiment. The present experiment calls for the detection of the oxygen lines in emission. Spectral differences of  $200^\circ \text{K}$  are expected between channels, as can be seen from Fig. 2. This difference can be greatly increased, by a factor of 10 or 20, by directing the antenna at the sun and detecting the lines as absorption lines, that is, Fraunhofer lines. The greater signal is obtained at the expense of requiring a means of locking on the sun at float altitude. Furthermore, two obvious drawbacks to the experiment are that nighttime flights are not possible, and a wide range of zenith angles will not be possible without very long flights. But the larger signal will enable one to distinguish variations more easily in the total oxygen absorption as a function of time.

2. Planetary Observations. No observations of the planets can be made at 5-mm wavelength, because of the oxygen attenuation from ground level. It is certainly possible, however, to detect planetary radiation at typical balloon altitudes, provided that the frequency chosen falls between the oxygen resonances, for example as in channel 3 (Table 1) of the present experiment. This experiment requires, of course, an accurate guidance system to acquire the planet, and a large parabolic reflector of high surface accuracy. An antenna diameter of 15-20 feet would suffice.

3. Satellite Observations. Preliminary to detailed spectral measurements in an earth-orbiting satellite, an initial experiment with a wideband

radiometer would be desirable to define the background temperature of the earth's upper atmosphere on a global scale. A bandwidth of 100-200 Mc/sec, centered between resonance lines, would be sufficient to define temperature variations in the upper atmosphere as a function of latitude. A polar orbit would be desirable for this experiment. As previously stated, a solid-state local oscillator would be mandatory for this program.

## V. THESES AND PUBLICATIONS

The first year of this program has been entirely devoted to the design and construction of equipment and no theses or publications have resulted.

## VI. PERSONNEL

The following list comprises the research personnel who were supported in part by this grant.

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